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Changes in soil quality after converting *Pinus* to *Eucalyptus* plantations in southern China

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Abstract. Vegetation plays a key role in maintaining soil quality, but long-term changes in soil quality due to plant species change and successive planting are rarely reported. Using the space-for-time substitution method, adjacent plantations of *Pinus* and first, second, third and fourth generations of *Eucalyptus* in Guangxi, China were used to study changes in soil quality caused by converting *Pinus* to *Eucalyptus* and successive *Eucalyptus* planting. Soil chemical and biological properties were measured and a soil quality index was calculated using principal component analysis. Soil organic carbon, total nitrogen, alkaline hydrolytic nitrogen, microbial biomass carbon, microbial biomass nitrogen, cellobiosidase, phenol oxidase, peroxidase and acid phosphatase activities were significantly lower in the first and second generations of *Eucalyptus* plantations compared with *Pinus* plantation, but they were significantly higher in the third and fourth generations than in the first and second generations and significantly lower than in *Pinus* plantation. Soil total and available potassium were significantly lower in *Eucalyptus* plantations (1.8–2.5 $g\,kg^{-1}$ and 26–66 $mg\,kg^{-1}$) compared to the *Pinus* plantation (14.3 $g\,kg^{-1}$ and 92 $mg\,kg^{-1}$), but total phosphorus was significantly higher in *Eucalyptus* plantations (0.9–1.1 $g\,kg^{-1}$) compared to the *Pinus* plantation (0.4 $g\,kg^{-1}$). As an integrated indicator, soil quality index was highest in the *Pinus* plantation (0.92) and lowest in the first and second generations of *Eucalyptus* plantations (0.24 and 0.13). Soil quality index in the third and fourth generations (0.36 and 0.38) was between that in *Pinus* plantation and in first and second generations of Eucalyptus plantations. Changing tree species, reclamation and fertilization may have contributed to the change observed in soil quality during conversion of *Pinus* to *Eucalyptus* and successive *Eucalyptus* planting. Litter retention, keeping understorey coverage, and reducing soil disturbance during logging and subsequent establishment of the next rotation should be considered to help improving soil quality.

1 Introduction

Vegetation plays a key role in soil development due to its influence on nutrient cycling, hydrological processes and soil erosion (de la Paix et al., 2013; Zhao et al., 2013). Degradation of soil quality is a serious problem (Miao et al., 2012; Zhao et al., 2013). *Eucalyptus* is an important tree species for afforestation in tropical and subtropical regions and has been introduced to many countries around the world. In southern China, millions of hectares of degraded land, cropland and natural secondary forest have been converted into *Eucalyptus* plantations and successive planting has been undertaken (Wen et al., 2009). However, due to nutrient limitations in many areas (LeBauer and Treseder, 2008) and a high demand for nutrients by *Eucalyptus* (Laclau et al., 2010), this kind of land use change may exhaust soil nutrients and decrease soil quality (Yu et al., 2000b). Inappropriate plantation management also accelerates the decline in soil quality (Yu et al., 2009). There is an urgent need to assess the effects that *Eucalyptus* planting has on soil quality since it plays a key role in sustaining forest productivity.

Soil quality includes soil physical, chemical and biological properties, as well as soil processes and their interactions (Andrews and Carroll, 2001). Many studies have focused on

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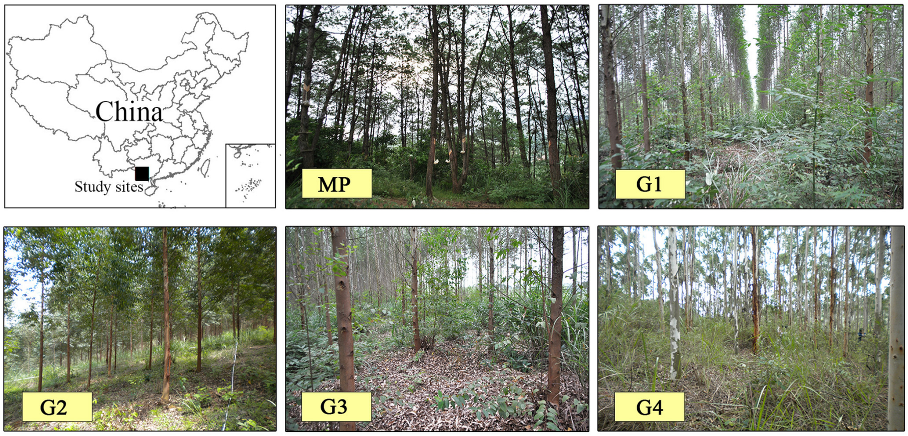

Figure 1. Study site and pictures of the *Pinus* and the successive *Eucalyptus* plantations. MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the first, second, third and fourth generation *Eucalyptus* plantations, respectively.

soil physic-chemical properties (Garay et al., 2004; Muñoz-Rojas et al., 2012; Parras-Alcántara et al., 2013), microbial communities (Wu et al., 2012) or enzyme activities (Wang et al., 2008), which only reflect some aspects of soil quality. A soil quality index (SQI) was proposed for quantifying the combined biological, chemical and physical response of soil to land use and soil/crop management practices (Andrews and Carroll, 2001; Andrews et al., 2002). It provides an intelligible and more holistic measurement of soil quality and, in recent years, the SQI has been used to assess the impacts of land use change, forest and cropland management and ecological restoration (Navas et al., 2011; Morugán-Coronado et al., 2013; Tesfahunegn, 2013). Methods used to calculate SQI include expert opinion and principal component analysis (PCA) (Andrews et al., 2002), with the latter more widely used in recent studies (Navas et al., 2011).

The ecological consequences of *Eucalyptus* planting are important and have been studied in depth. For example, it was reported that soil organic carbon, nitrogen, microbial biomass and the metabolic quotient were significantly lower in *Eucalyptus* plantations compared to natural and regenerated forests or pastures (Behera and Sahani, 2003; Sicardi et al., 2004; Araújo et al., 2010; Chen et al., 2013). It was also found that the conversion of native savanna or sugarcane fields to *Eucalyptus* plantations did not cause impacts on soil organic carbon, microbial biomass carbon or nitrogen contents (Binkley et al., 2004). Fialho and Zinn (2014) compiled paired-plot studies on how soil organic carbon stocks under native vegetation change after planting fast-growth *Eucalyptus* species in Brazil and found that *Eucalyptus* plantations on average had no net effect on soil organic carbon stocks. The results of these different studies were not consistent and the effect of successive *Eucalyptus* planting has rarely been reported.

Here we accessed the effects of converting *Pinus* to *Eucalyptus* and subsequent successive *Eucalyptus* planting on soil quality by examining adjacent plantations of local *Pinus massoniana* Lamb. (*Pinus*) and first, second, third and fourth generations of *Eucalyptus urophylla x grandis* (*Eucalyptus*). The changes in soil quality were investigated by measuring the soil chemical and biological properties and by calculating a SQI using the PCA method for each plantation. Exhaustion of soil nutrients was the main problem considered in the studied *Eucalyptus* plantation; soil physical attributes were not considered in this study. The study aimed to test the effect on soil bio-chemical quality after (1) converting *Pinus* to *Eucalyptus* plantations and (2) successive *Eucalyptus* planting with rotation time of 5 years in southern China.

2 Materials and methods

2.1 Study area

This study was conducted at Fusui, Guangxi, China (22°14′–22°21′ N, 107°47′–107°56′ E; Fig. 1). Elevation of study sites was between 140 and 250 m above sea level. The dominant aspect of slopes was southeast, with slope below 15°. The region has a typical subtropical monsoon climate with mean annual temperature of 21.2–22.3 °C. Annual rainfall is 1100–1300 mm, concentrated during June–August. Soils in the region are mainly lateritic red earth with a profile depth of more than 80 cm. Soil pH ranged from 4 to 5 (Chen et al., 2013).

Before the 1980s, this area was dominated by *Pinus massoniana* Lamb. (*Pinus*), with 30-year rotation (clearing and new planting), used for fire wood, timber and oil production. In the 1980s, fast-growing *Eucalyptus urophylla x grandis* (*Eucalyptus*) with a 5-year rotation period began to replace *Pinus*. The first generation of *Eucalyptus* was planted with a density of about 1400 trees ha^{-1} after clear-cutting, fire clearance and full reclamation (plowed to 50 cm depth). The second generation of *Eucalyptus* was regenerated by

Table 1. Soil quality indicator scores (mean ± standard error) for soil samples taken from the *Pinus* and *Eucalyptus* plantations.

	MP	G1	G2	G3	G4
SOC	0.962 ± 0.022^{a}	0.206 ± 0.048^{bc}	0.064 ± 0.038^{c}	0.328 ± 0.011^{b}	0.419 ± 0.103^{b}
TN	0.918 ± 0.053^{a}	0.104 ± 0.022^{d}	0.022 ± 0.011^{d}	0.494 ± 0.022^{c}	0.649 ± 0.037^{b}
TK	0.929 ± 0.056^{a}	0.003 ± 0.002^{b}	0.020 ± 0.004^{b}	0.018 ± 0.002^{b}	0.052 ± 0.006^{b}
AK	0.996 ± 0.002^{a}	0.450 ± 0.010^{c}	0.614 ± 0.017^{b}	0.121 ± 0.013^{d}	0.032 ± 0.020^{e}
CBH	0.972 ± 0.014^{a}	0.816 ± 0.025^{ab}	0.252 ± 0.142^{c}	0.491 ± 0.016^{c}	0.528 ± 0.044^{bc}
PO	0.861 ± 0.080^{a}	0.032 ± 0.017^{d}	0.062 ± 0.009^{cd}	0.235 ± 0.021^{bc}	0.369 ± 0.026^{b}
POD	0.831 ± 0.085^{a}	0.039 ± 0.015^{c}	0.022 ± 0.020^{c}	0.260 ± 0.004^{b}	0.317 ± 0.033^{b}
ACP	0.938 ± 0.035^{a}	0.038 ± 0.022^{c}	0.084 ± 0.018^{c}	0.227 ± 0.031^{b}	0.239 ± 0.024^{b}

MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the first, second, third and fourth generation *Eucalyptus* plantations, respectively. SOC, soil organic carbon; TN, total nitrogen; TK, total potassium; AK, available potassium; CBH, cellobiosidase; PO, phenoloxidase; POD, peroxidase and ACP, acid phosphatase. Means followed by the same letter (a–d) within a row are not significantly different at $p < 0.05$.

sprouts. The third generation of *Eucalyptus* was planted with seedlings after strip reclamation (50 cm depth). Finally, the fourth generation was regenerated by sprouts again. Leaves, branch and bark litter were kept in the plantation during the plant growth period. However, at harvest time, most branch litter was removed and burned before the next rotation, and soil erosion happened easily due to the lack of soil protection during the crop transition periods.

Before *Eucalyptus* planting, base fertilizer (500 g seedling^{-1}, N : P : K = 10 : 15 : 5) was added into a 20 cm depth soil hole under each new *Eucalyptus* tree and covered with soil. Then, 6, 12 and 24 months after planting, 250, 500 and 500 g, respectively, of fertilizer (N : P : K = 15 : 10 : 8) per tree was separately added in soil holes that were 30 cm away from each tree. Herbicide (glyphosate) was applied once a year during the first 3 years after *Eucalyptus* planting and consequently the coverage of understory plants was less than 50 %. However, the understory coverage increased gradually during the fourth and fifth years after *Eucalyptus* planting. During sampling time, tree, shrub and grass cover in the *Pinus* plantation was about 60, 25 and 70 %, respectively. Tree, shrub and grass cover in the *Eucalyptus* plantations was similar, about 40, 10 and 45 %, respectively. The litter layer was about 3 cm in the *Pinus* plantation and 1 cm deep in the *Eucalyptus* plantations.

2.2 Experimental design and sampling

The adjacent plantations of local *Pinus* and first, second, third and fourth generations of *Eucalyptus* at the Dongmen Forestry Farm were selected (Fig. 1) to represent *Pinus* planting and first, second, third and fourth generations of successive *Eucalyptus* planting. Three 20 m × 20 m plots were randomly selected and marked out at each plantation site, with an average distance of 20 m between plots. During soil sampling, the ages of *Pinus* and *Eucalyptus* was 20 and 3 years, respectively.

In October 2010, soil from the top 0–10 cm layer was collected from the study sites. Ten soil cores were collected at randomly selected points at each plot using a 3.6 cm diameter soil auger and mixed together as a composite sample. Three composite samples were collected at each point. Stones and roots were removed from the soil samples by hand and soil samples were sieved through 2 mm sieves. Soil samples were stored at 4 °C for soil microbial biomass and enzyme activity analyses, or air dried for chemical analyses.

2.3 Soil chemical and biological analyses

Soil water content was determined gravimetrically after oven-drying at 105 °C for 24 h in order to correct sample weights in biochemical property measurements. Soil pH was measured in deionized water (1 : 2.5 w/v) using a Delta 320 pH-meter (Mettler-Toledo Instruments (Shanghai) Co., Ltd.). Soil organic carbon (SOC) was measured using the Walkley and Black wet oxidation method as outlined in Bao (2000). Soil total nitrogen (TN) was determined by combustion in a Vario EL III Elemental Analyser (Elementar Analysensysteme GmbH, Germany). Soil alkaline hydrolytic nitrogen (AN) was measured according to Bao (2000). For the assessment of AN, 1 g of air-dried soil was incubated in 5 mL sodium hydroxide solution (1.2 M) in the outside ring of an airtight Conway diffusion cell; 3 mL boric acid (0.3 M) were added to the inner well at 40 °C for 24 h. With methyl red-bromocresol green as indicator, 0.01 M hydrochloric acid was used to titrate ammonia absorbed in the boric acid. For total phosphorus (TP) and total potassium (TK), air-dried soil samples were digested using 18.4 M sulfuric acid (1 : 10 w/v) and 12.7 M perchloric acid at 275 °C for 6 h, TP and TK were measured using a Prodigy High Dispersion ICP-OES (Teledyne Technologies Incorporated, USA). Available phosphorus (AP) was measured after extraction with 0.05 N sulfuric and 0.025 N hydrochloric acids (1 : 5 w/v), with shaking during 5 min. Available potassium (AK) was measured after extraction with 1 N ammonium acetate solution (1 : 10 w/v), shaken for 30 min (Bao, 2000). AP and AK were measured using the Prodigy High Dispersion ICP-OES.

Soil microbial biomass carbon and nitrogen (MBC and MBN, respectively) were estimated using the chloroform fumigation extraction method (Vance et al., 1987). Soil β-glucosidase (BG), phenol oxidase (PO), peroxidase (POD) and acid phosphatase (ACP) activities were measured according to Waldrop et al. (2000). Soil protease (PRO) activity was estimated according to Ladd and Butler (1972). Soil urease (URE) activity was assessed according to Kandeler and Gerber (1988). Soil cellobiosidase (CBH) activity was measured using the fluorimetric method according to Saiya-Cork et al. (2002).

2.4 Calculation of the soil quality index

The SQI was calculated according to Andrews and Carroll (2001). Three steps were involved in the elaboration of this quality index: (i) definition of a minimum data set (MDS), (ii) assignment of a score to each indicator by linear scoring functions and (iii) data integration into an index.

Three steps were used to identify the MDS in our study. (1) Data screening: one-way analysis of variance was performed for soil chemical and biological properties; only variables with significant differences between treatments ($p < 0.05$) were chosen for the next step. (2) Selection of representative variables: PCA was performed on the variables chosen from step (1); only principal components (PCs) that explained at least 5 % of the variation in the data up to 85 % of the cumulative variation were examined, within each PC, only weighted factors with absolute values within 10 % of the highest weight were retained for the MDS. (3) Redundancy reduction: multivariate correlation coefficients were used to determine the strength of the relationships among variables. Highly correlated variables (correlation coefficient > 0.70) were considered redundant and candidates for elimination from the data set. In order to choose variables within well-correlated groups, we summed the absolute values of the correlation coefficients for these variables and assumed that the variable with the highest correlation sum best represented the group. The choice among well-correlated variables was also based on the published references and expert opinion about the soils and sites (Xu, 2000; Wang et al., 2008; Yu et al., 2009). Any uncorrelated, highly weighted variables were considered important and retained in the MDS.

Linear scoring was used in our study. Indicators were ranked in ascending or descending order depending on whether a higher value was considered "good" or "bad" in terms of soil function. In our study, all variables were "more is better". The linear scoring function used for converting measured values to scored values is as follows (Zheng et al., 2005):

$$S_{ij} = \frac{V_{ij} - V_{i\min}}{V_{i\max} - V_{i\min}}$$

where S_{ij} is the score of soil variable i of sample j, V_{ij} is the observed variable value of sample j, $V_{i_{\max}}$ is the highest value of variable i, and $V_{i_{\min}}$ is the lowest value of variable i.

The scores of the indicators (Table 1) were integrated into a SQI according to Andrews et al. (2002) as follows:

$$\mathrm{SQI} = \sum_{i=1}^{n} \frac{S_i}{n},$$

where S_i is the score assigned to indicator i, and n is the number of indicators included in the MDS.

2.5 Statistical analyses

One-way variance analyses were used to test the significant differences in soil chemical and biological properties and SQIs among these treatments. Normality of the data was tested using the Kolmogorov–Smirnov test and the soil indicators obeyed standard normal distribution. Tukey's test was used for multiple comparison analysis. All statistical analyses were performed using SPSS 10.0 (SPSS Inc., Chicago, IL, USA) and SigmaPlot for Windows version 11.0 (Systa Software Inc.). The three plots established per site do not constitute true replicates, because they are located within the same area of the five plantations (*Pinus*, first, second, third and fourth generations *Eucalyptus* plantations). However, these plantation stands occur in similar topographic conditions and soil parent material, and were similar in planting history (*Pinus* plantation before the 1980s), which allowed us to consider them as different treatments.

3 Results

3.1 Soil chemical properties

SOC, TN and AN ranges at our study sites were 10.8–26.9 g kg^{-1}, 0.9–1.6 g kg^{-1} and 41.4–60.3 mg kg^{-1}, respectively. They were high in the *Pinus* plantation, low in the first and second generations of *Eucalyptus* plantations, and moderate in the third and fourth generations (Fig. 2a–c). SOC and TN in the fourth generation of *Eucalyptus* plantations were significantly lower than in the *Pinus* plantation, but significantly higher than in the second generation of *Eucalyptus* plantations. Soil AN in the fourth generation of *Eucalyptus* was significantly higher than in the second generation, but not different from that in the *Pinus* plantation.

Soil TP content was significantly lower in the *Pinus* plantation (0.41 g kg^{-1}) than in the *Eucalyptus* plantations (0.90–1.07 g kg^{-1}). In the *Eucalyptus* plantations, soil TP content was significantly lower in the second generation than in the third and fourth generations (Fig. 2d). Soil AP content was 2.98 mg kg^{-1} in the *Pinus* plantation, which is lower than 5.03 and 5.14 mg kg^{-1} in the first and second generations of *Eucalyptus* plantations, respectively, a little higher than 2.56

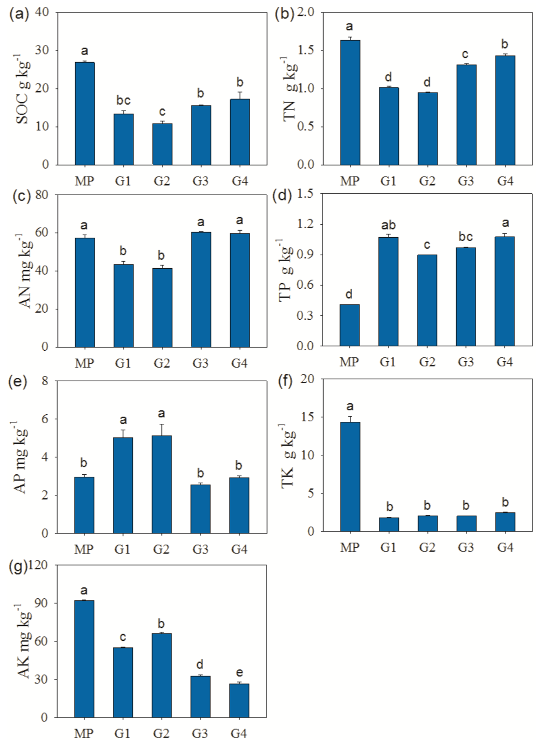

Figure 2. Soil chemical properties in the *Pinus* and the successive *Eucalyptus* plantations. MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the first, second, third and fourth generation *Eucalyptus* plantations, respectively. SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; TK, total potassium; AN, alkaline hydrolytic nitrogen; AP, available phosphorus and AK, available potassium. Soil chemical properties with the same letter are not significantly different at $p < 0.05$.

and 2.93 mg kg^{-1} in the third and fourth generations, respectively (Fig. 2e).

Soil TK and AK ranged from 1.8 to 6.3 g kg^{-1} and from 24 to 92 mg kg^{-1}, respectively. TK content was significantly lower in the *Eucalyptus* plantations than in the *Pinus* plantation, without significant differences between *Eucalyptus* generations (Fig. 2f). AK content was significantly higher in the *Pinus* plantation compared with in *Eucalyptus* plantations (Fig. 2g).

3.2 Soil microbial biomass carbon and nitrogen

Soil MBC and MBN contents ranged from 278 to 673 mg kg^{-1} and from 7 to 35 mg kg^{-1}, respectively. Soil MBC content was significantly lower in the first and second generation of *Eucalyptus* plantations than in the third and fourth generations (Fig. 3a). Soil MBN content was significantly lower in the second generation (Fig. 3b). The MBC / MBN ratio was significantly higher in the second generation *Eucalyptus* plantation than in other plantations (Fig. 3c).

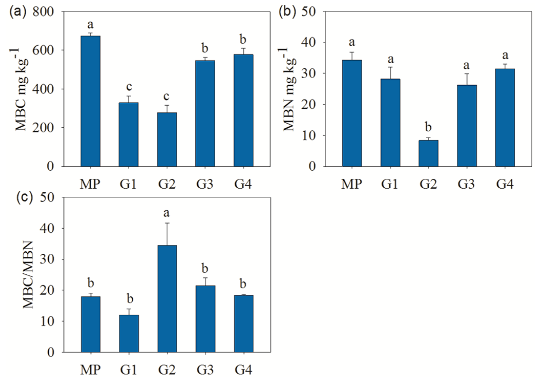

Figure 3. Soil microbial biomass carbon and nitrogen in the *Pinus* and the successive *Eucalyptus* plantations. MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the first, second, third and fourth generation *Eucalyptus* plantations, respectively. MBC, microbial biomass carbon and MBN, microbial biomass nitrogen. Microbial indicators with the same letter are not significantly different at $p < 0.05$.

3.3 Soil enzyme activities

BG activity was significantly higher in the *Pinus* plantation compared with in *Eucalyptus* plantations (Fig. 4a). Soil CBH, PO, POD, PRO and ACP activities were highest in the *Pinus* plantation, lowest in the first or second generations of *Eucalyptus* plantations and between the middle in the third or fourth generations of *Eucalyptus* plantations (Fig. 4b–f). Soil URE activity was significantly higher in the *Pinus* plantation than in the *Eucalyptus* plantations, with no significant differences among *Eucalyptus* plantations (Fig. 4g).

3.4 Changes in soil quality index

SQI was highest in the *Pinus* plantation (0.92) and lowest in the second generation of the *Eucalyptus* plantations (0.13). In the third and fourth *Eucalyptus* generations, SQI was significantly higher than in the second *Eucalyptus* generation (0.36 and 0.38, respectively, compared to 0.13), but still lower than in the *Pinus* plantation (0.92, Fig. 5).

4 Discussion

4.1 Decrease in soil quality in the first and second generations of Eucalyptus planting

Our study found that SOC, TN, AN, TK, AK, MBC, MBN and enzyme activities significantly decreased in the first and second generation *Eucalyptus* plantations after converting *Pinus* to *Eucalyptus* (Figs. 2–4). This is consistent with many studies which reported that SOC, TN, MBC, carbon metabolic activity and metabolic quotient were significantly lower in *Eucalyptus* plantations than in natural and regenerated forest or pastures (Behera and Sahani, 2003; Sicardi

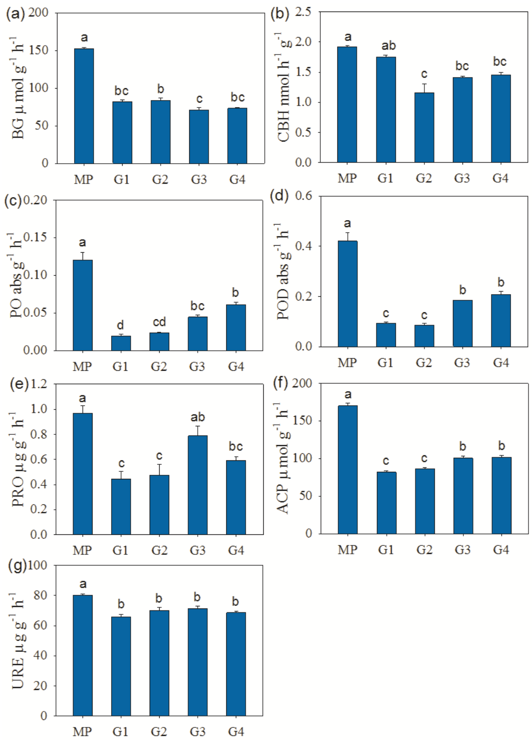

Figure 4. Soil enzyme activities in the *Pinus* and the successive *Eucalyptus* plantations. MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the first, second, third and fourth generation *Eucalyptus* plantations, respectively. BG, β-glucosidase; CBH, cellobiosidase; PO, phenoloxidase; POD, peroxidase; PRO, protease; URE, urease and ACP, acid phosphatase. Enzyme activities with the same letter are not significantly different at $p < 0.05$.

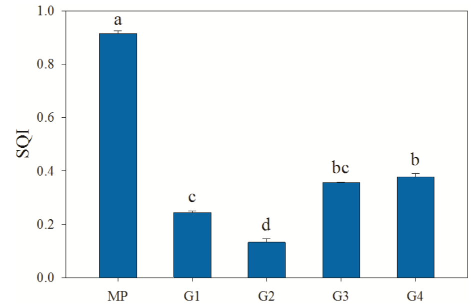

Figure 5. Soil quality index in the *Pinus* and the successive *Eucalyptus* plantations. MP, G1, G2, G3 and G4 refer to the *Pinus* plantation and the first, second, third and fourth generation *Eucalyptus* plantations, respectively. SQI, soil quality index. SQIs with the same letter are not significantly different at $p < 0.05$.

et al., 2004; Chen et al., 2013). However, in our study, soil TP was significantly higher in *Eucalyptus* plantation, which might be caused by fertilization in *Eucalyptus* plantations and the low mobility of phosphorus. The decreased soil quality in the first and second generations of *Eucalyptus* plantations after converting *Pinus* to *Eucalyptus* plantation may have been caused by tree species change, full reclamation, herbicide application, clear-cutting and short rotation.

Eucalyptus has a fast growth rate and a strong nutrient absorption capacity, which means that they absorb soil nutrients and store them in the biomass efficiently (Laclau et al., 2005), resulting in lower nutrient contents in the soil (Fig. 2). Tesfaye et al. (2014) evaluated seven tree species for fuelwood and soil restoration and found that *Eucalyptus* presented the highest growth rates and biomass, but depleted soil nitrogen. The depletion of nitrogen in soils under *Eucalyptus* plantations was also found by Wen et al. (2009). The lower soil nutrient contents in the second generation *Eucalyptus* plantation may lead to lower soil microbial biomass and enzyme activities and a higher MBC / MBN ratio (Figs. 3, 4).

Full reclamation normally impacts the soil structure, exposes more aggregates and accelerates organic matter decomposition (Zinn et al., 2002), which would lead to lower soil organic matter contents in the *Eucalyptus* plantations. Understorey vegetation may provide a better microcosm for microorganisms and alleviate rainfall-induced erosion and nutrient leaching (Yu et al., 2000a). In our study, herbaceous vegetation was treated with herbicide during the first 3 years of the *Eucalyptus* planting exposing the uncovered soils to erosion.

At harvest, clear-cutting totally destroyed plant coverage and the subsequent fire clearance burned all the residues and the litter layer, which resulted in bare ground prior to *Eucalyptus* planting. Soil erosion and nutrient leaching can occur during heavy rainfall if there is no protection from plant and litter layers (Yu et al., 2000a). Fire also removes significant amounts of organic matter (Certini, 2005) and nutrients are lost through volatilization (Fisher and Binkley, 2000). Soil microbial biomass decreases during fire because of increased decay and death of heat-sensitive microbes or through alterations of soil physic-chemical properties (De Marco et al., 2005). These could have been the causes for the bio-chemical depletion observed in soils that underwent *Pinus* to *Eucalyptus* conversion.

Eucalyptus cultivation rotations are very short (only 5 years) compared to *Pinus* (30 years), which means that there is frequent biomass loss in *Eucalyptus* plantations. Furthermore, short rotations have an impact on the nutrient absorption patterns and the soil nutrient returns. During the early stages of plant life, nutrient absorption is high and litter production is small, but as the plant gets older nutrient absorption decreases and litter production increases (Xu, 2000). The 5-year rotation of *Eucalyptus* plantations and frequent cutting led to severe soil nutrient loss.

4.2 Increase in soil quality in the third and fourth generations of Eucalyptus planting

Our results showed that after the sudden decline following converting *Pinus* to *Eucalyptus*, SOC, TN, MBC, CBH, PO, POD and ACP activities recovered in the third and fourth generations, albeit lower than that in the native *Pinus* plantation (Figs. 2–4). This is inconsistent with Yu et al. (2000b), who recorded that soil physical and chemical properties decreased during successive *Eucalyptus* planting. However, Lima et al. (2006) recorded an increasing soil organic matter trend as the plantation aged after *Eucalyptus* afforestation of degraded pastures. The inconsistency between these studies might be caused by different climate, soil properties, *Eucalyptus* species and management practices amongst the study sites. The recovery of soil quality in the third and fourth generation *Eucalyptus* plantations may be attributed to reduced soil disturbance and fertilizer application.

Soil disturbance caused by strip reclamation in the third generation *Eucalyptus* plantation was much smaller than that due to full reclamation during the conversion from *Pinus* to *Eucalyptus*, which may have led to a reduction in soil organic matter decomposition, soil erosion and nutrient leaching. The decreased soil erosion risk, nutrient leaching and organic matter decomposition rate helped in improving soil organic matter accumulation and nutrient levels (Yu et al., 2000a).

Fertilization could increase plant growth and litter input (Madeira et al., 1995), so improving soil quality. If soil nutrient inputs through fertilization and litter fall equal the output caused by erosion, plant absorption and leaching, then soil quality would reach a steady status (Xu, 2000). Our results suggest a recovery in soil quality after the third and fourth generations of *Eucalyptus* planting (Fig. 5). To better understand the impacts of successive *Eucalyptus* planting on soil quality, evaluation of more generations of *Eucalyptus* plantations is needed.

5 Conclusions

Findings from our study suggest that soil quality decreased significantly in the first and second generation *Eucalyptus* plantations after converting *Pinus* to *Eucalyptus* plantations, partially recovering in the following third and fourth generations. Changes in tree species, reclamation, herbicide application and long-term fertilization might have contributed to the changes observed in the soil quality during successive *Eucalyptus* planting. Our results emphasize the importance of long-term soil quality monitoring. Improving management practices, such as maintenance of litter and herbaceous cover and reduction of soil disturbance during logging and subsequent establishment of the next planting rotation, should be considered to maintain soil quality.

Author contributions. H. Zheng and Z. Y. Ouyang designed the experiment and K. Zhang, F. L. Chen, and Y. Wang carried it out. Y. F. Wu, J. Lan, M. Fu and X. W. Xiang helped collecting soil samples and gave suggestion about the experiment. K. Zhang and H. Zheng prepared the paper.

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References

Andrews, S. S. and Carroll, C. R.: Designing a soil quality assessment tool for sustainable agroecosystem management, Ecol. Appl., 11, 1573–1585, 2001.

Andrews, S. S., Karlen, D. L., and Mitchell, J. P.: A comparison of soil quality indexing methods for vegetable production systems in Northern California, Agr. Ecosyst. Environ., 90, 25–45, 2002.

Araújo, A. S. F., Silva, E. F. L., Nunes, L. A. P. L., and Carneiro, R.F.V.: The effect of converting tropical native savanna to Eucalyptus grandis forest on soil microbial biomass, Land Degrad. Dev., 21, 540–545, 2010.

Bao, S. D.: Soil Agro-chemical Analysis, China Agriculture Press, Beijing, 2000 (in Chinese).

Behera, N. and Sahani, U.: Soil microbial biomass and activity in response to Eucalyptus plantation and natural regeneration on tropical soil, Forest Ecol. Manag., 174, 1–11, 2003.

Binkley, D., Kaye, J., Barry, M., and Ryan, M. G.: First-rotation changes in soil carbon and nitrogen in a Eucalyptus plantation in Hawaii, Soil Sci. Soc. Am. J., 68, 1713–1719, 2004.

Certini, G.: Effects of fire on properties of forest soils: a review, Oecologia, 143, 1–10, 2005.

Chen, F. L., Zheng, H., Zhang, K., Ouyang, Z. Y., Lan, J., Li, H. L., and Shi, Q.: Changes in soil microbial community structure and metabolic activity following conversion from native Pinus massoniana plantations to exotic Eucalyptus plantations, Forest Ecol. Manag., 291, 65–72, 2013.

de la Paix, M. J., Lanhai, L., Xi, C., Ahmed, S., and Varenyam, A.: Soil degradation and altered flood risk as a consequence of deforestation, Land Degrad. Dev., 24, 478–485, 2013.

De Marco, A., Gentile, A. E., Arena, C., and De Santo, A. V.: Organic matter, nutrient content and biological activity in burned and unburned soils of a Mediterranean maquis area of southern Italy, Int. J. Wildland Fire, 14, 365–377, 2005.

Fialho, R. C. and Zinn, Y. L.: Changes in soil organic carbon under Eucalyptus plantations in Brazil: a comparative analysis, Land Degrad. Dev., 25, 428–437, 2014.

Fisher, R. F. and Binkley, D.: Fire effects, 241–261, edited by: Fisher, R. F. and Binkley, D., in : Ecology and management of forest soils, 3rd edition, John Wiley & Sons Inc, New York, 2000.

Garay, I., Pellens, R., Kindel, A., Barros, E., and Franco, A. A.: Evaluation of soil conditions in fast-growing plantations of Eucalyptus grandis and Acacia mangium in Brazil: a contribution to the study of sustainable land use, Appl. Soil Ecol., 27, 177–187, 2004.

Kandeler, E. and Gerber, H.: Short-term assay of soil urease activity using colorimetric determination of ammonium, Biol. Fert. Soils, 6, 68–72, 1988.

Laclau, J. P., Ranger, J., Deleporte, P., Nouvellon, Y., Saint-Andre, L., Marlet, S., and Bouillet, J. P.: Nutrient cycling in a clonal stand of Eucalyptus and an adjacent savanna ecosystem in Congo 3, Input-output budgets and consequences for the sustainability of the plantations, Forest Ecol. Manag., 210, 375–391, 2005.

Laclau, J. P., Ranger, J., Goncalves, J. L. D., Maquere, V., Krusche, A. V., M'Bou, A. T., Nouvellon, Y., Saint-Andre, L., Bouillet, J. P., Piccolo, M. D., and Deleporte, P.: Biogeochemical cycles of nutrients in tropical Eucalyptus plantations: Main features shown by intensive monitoring in Congo and Brazil, Forest Ecol. Manag., 259, 1771–1785, 2010.

Ladd, J. N. and Butler, J. H. A.: Short-term assays of soil proteolytic enzyme activities using proteins and dipeptide derivatives as substrates, Soil Biol. Biochem., 4, 19–30, 1972.

LeBauer, D. S. and Treseder, K. K.: Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed, Ecology, 89, 371–379, 2008.

Lima, A. M. N., Silva, I. R., Neves, J. C. L., Novais, R. F., Barros, N. F., Mendonca, E. S., Smyth, T. J., Moreira, M. S., and Leite, F. P.: Soil organic carbon dynamics following afforestation of degraded pastures with Eucalyptus in southeastern Brazil, Forest Ecol. Manag., 235, 219–231, 2006.

Madeira, M., Araújo, M. C., and Pereira, J. S.: Effects of water and nutrient supply on amount and on nutrient concentration of litterfall and forest floor litter in Eucalyptus globulus plantations, Plant Soil, 168, 287–295, 1995.

Miao, C., Yang, L., Chen, X., and Gao, Y.: The vegetation cover dynamics (1982–2006) in different erosion regions of the Yellow River basin, China, Land Degrad. Dev., 23, 62–71, 2012.

Morugán-Coronado, A., Arcenegui, V., García-Orenes, F., Mataix-Solera, J., and Mataix-Beneyto, J.: Application of soil quality indices to assess the status of agricultural soils irrigated with treated wastewaters, Solid Earth, 4, 119–127, doi:10.5194/se-4-119-2013, 2013.

Muñoz-Rojas, M., Jordán, A., Zavala, L. M., De la Rosa, D., Abd-Elmabod, S. K., and Anaya-Romero, M.: Organic carbon stocks in Mediterranean soil types under different land uses (Southern Spain), Solid Earth, 3, 375–386, doi:10.5194/se-3-375-2012, 2012.

Navas, M., Benito, M., Rodríguez, I., and Masaguer, A.: Effect of five forage legume covers on soil quality at the Eastern plains of Venezuela, Appl. Soil Ecol., 49, 242–249, 2011.

Parras-Alcántara, L., Martín-Carrillo, M., and Lozano-García, B.: Impacts of land use change in soil carbon and nitrogen in a Mediterranean agricultural area (Southern Spain), Solid Earth, 4, 167–177, doi:10.5194/se-4-167-2013, 2013.

Saiya-Cork, K. R., Sinsabaugh, R. L., and Zak, D. R.: The effects of long term nitrogen deposition on extracellular enzyme activity in an Acer saccharum forest soil, Soil Biol. Biochem., 34, 1309–1315, 2002.

Sicardi, M., García-Préchacb, F., and Frionic, L.: Soil microbial indicators sensitive to land use conversion from pastures to commercial Eucalyptus grandis (Hill ex Maiden) plantations in Uruguay, Appl. Soil Ecol., 27, 125–133, 2004.

Tesfahunegn, G. B.: Soil quality indicators response to land use and soil management systems in Northern Ethiopia's catchment, Land Degrad. Dev., doi:10.1002/ldr.2245, 2013

Tesfaye, M. A., Bravo-Oviedo, A., Bravo, F., Kidane, B., Bekele, K., and Sertse, D.: Selection of tree species and soil management for simultaneous fuelwood production and soil rehabilitation in the Ethiopian central highlands, Land Degrad. Dev., doi:10.1002/ldr.2268, 2014.

Vance, E. D., Brookes, P. C., and Jenkinson, D. S.: An extraction method for measuring soil microbial biomass C, Soil Biol. Biochem., 19, 703–707, 1987.

Waldrop, M. P., Balser, T. C., and Firestone, M. K.: Linking microbial community composition to function in a tropical soil, Soil Biol. Biochem., 32, 1837–1846, 2000.

Wang, Q. K., Wang, S. L., and Liu, Y.: Responses to N and P fertilization in a young Eucalyptus dunnii plantation: Microbial properties, enzyme activities and dissolved organic matter, Appl. Soil Ecol., 40, 484–490, 2008.

Wen, Y. G., Zheng, X., Li, M. C., Xu, H. G., Liang, H. W., Huang, C. B., Zhu, H. G., and He, B.: Effects of eucalypt plantation replacing Masson pine forest on soil physiochemical properties in Guangxi, southern China, Journal of Beijing Forestry University, 31, 145–148, 2009 (in Chinese).

Wu, J. P., Liu, Z. F., Sun, Y. X., Zhou, L. X., Lin, Y. B., and Fu, S.L.: Introduced Eucalyptus urophylla plantations change the composition of the soil microbial community in subtropical China, Land Degrad. Dev., 24, 400–406, 2012.

Xu, D. P.: An approach to nutrient balance in tropical and south subtropical short rotation plantations, 27–35, edited by: Yu, X. B., in: Studies on long-term productivity management of Eucalyptus plantation, China Forestry Publishing House, Beijing, 2000 (in Chinese).

Yu, F. K., Huang, X. H., Wang, K. Q., and Duang, C. Q.: An overview of ecological degradation and restoration of Eucalyptus plantations, Chinese Journal of Eco-Agriculture, 17, 393–398, 2009 (in Chinese).

Yu, X. B., Chen, Q. B., Wang, S. M., and Mo, X. Y.: Research on land degradation in forest plantation and preventive strategies, 1–7, edited by: Yu, X. B., in: Studies on long-term productivity management of Eucalyptus plantation, China Forestry Publishing House, Beijing, 2000a (in Chinese).

Yu, X. B., Yang, G. Q., and Li, S. K.: Study on the changes of soil properties in Eucalyptus plantation under continuous-planting practices, 94–103, edited by: Yu, X. B., in: Studies on long-term productivity management of Eucalyptus plantation, China Forestry Publishing House, Beijing, 2000b (in Chinese).

Zhao, G., Mu, X., Wen, Z., Wang, F., and Gao, P.: Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China, Land Degrad. Dev., 24, 499–510, 2013.

Zheng, H., Ouyang, Z. Y., Wang, X. K., Miao, H., Zhao, T. Q., and Peng, T. B.: How different reforestation approaches affect red soil properties in Southern China, Land Degrad. Dev., 16, 387–396, 2005.

Zinn, Y. L., Resck, D. V. S., and Silva, J.E. da: Soil organic carbon as affected by afforestation with Eucalyptus and Pinus in the Cerrado region of Brazil, Forest Ecol. Manag., 166, 285–294, 2002.